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Solar System Exploration Survey, 2013-2022

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Future Io Exploration for 2013-2022 and Beyond, Part 1: Justification and Science Objectives

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I. IO SHOULD BE A PRIORITY FOR FUTURE EXPLORATION

Io is one of the most intriguing bodies in the Solar System, for intrinsic and extrinsic reasons. Intrinsically, there is much to be learned from the only known body to exhibit ongoing volcanic, tectonic, and gradational processes operating at rates comparable to (or exceeding) those on the Earth. The extrinsic interest comes from the insights that Io provides into wider issues in planetary science.

Io's Intrinsic Interest

Jupiter's satellite Io is the most geologically dynamic solid body in the Solar System, including Earth. Io undergoes severe tidal heating, induced by the orbital eccentricity forced by Jupiter and the 4:2:1 Laplace resonance between Io, Europa, and Ganymede. Global heat flow is estimated at >2 W m^{-2}, compared to the 0.06 W m^{-2} average for Earth. This one remarkable number presages a huge variety of interconnected phenomena operating at a scale not seen active anywhere else in our Solar System. Io offers an extremely rich array of geophysical, geological, geochemical, atmospheric, and magnetospheric phenomena. Diurnal tidal flexing amplitudes may reach ~100 meters, dissipating huge amounts of heat in the interior, although the sites and mechanisms of the dissipation are still unidentified. Lavas of poorly known composition inundate the surface, while volcanic plumes feed a tenuous, inhomogeneous atmosphere controlled by a combination of volcanic outgassing, the formation of surface frosts and the sublimation of these frosts. Complementing Io's pervasive volcanic landforms, the surface is studded with some of the Solar System's most dramatic mountains, and by scarps of both tectonic and erosional origin.

Most remarkably, geology can be observed as it happens on Io, and thus we are not restricted, as on other planetary bodies, to reconstructing geological processes from their long-dead remains. These processes occur at a variety of time-scales that make changes observable by near-by spacecraft. We can watch erupting plumes cover the surface with pyroclastic debris, as observed at the Tvashtar volcano during the February 2007 flyby of NASA's *New Horizons* spacecraft. We can observe lava flows advance across the surface, as was done (in a limited fashion) by NASA's *Galileo* spacecraft between 1999 and 2001. We can track chemical changes as surface materials anneal over time, and with better temporal and spatial coverage, we may also be able to watch tectonic and erosional processes at work.

Io supplies the Jovian magnetosphere with neutral gas, plasma, and dust. It is the major source of plasma in the magnetosphere. *New Horizons* has observed Iogenic plasma deep in the magnetotail, over 1000 Jovian radii from the planet. The processes by which these materials leave Io and subsequently evolve are complex and still poorly understood. Io is so energetic that many Io-related processes are observable from Earth, including thermal emission from its volcanoes, large-scale albedo changes from volcanic plume activity, large scale plume gas and dust canopies, temporal changes in its atmosphere, aurora, and the ionized and neutral clouds that populate the inner magnetosphere. Thus, much can be learned relatively inexpensively from Earth's surface or from Earth orbit, although some fundamental advances will require new spacecraft missions.

Finally, as one of the most spectacular places in the Solar System, Io has unique public appeal, and Io exploration offers many opportunities to attract and engage public interest in planetary science.

Extrinsic Interest: History and Mechanics of Tidal Heating

Io is the best place in the Solar System to study tidal heating, a process that is fundamental to the evolution of giant planet satellite systems, and one that may greatly expand the habitability zone

in extrasolar systems. By understanding Io, where manifestations of tidal heating are displayed to extremes and are easily observed, we can better understand the importance of tidal heating in a wide range of circumstances, including the history of satellites in our own Solar System, to the possibility of life-sustaining tidal heating elsewhere in the universe. Io is directly linked to the evolution of the one of most promising sites for extraterrestrial life, Europa (the primary target of the NASA-ESA Europa-Jupiter System Mission, EJSM), via the coupled orbital evolution of the two bodies. Jovian tidal forces act more strongly on Io than on Europa, but the Laplace resonance between the bodies helps transfer energy to Europa. Io's current heat flow appears to be at least a factor of two higher than sustainable by steady-state orbital evolution, suggesting that time-variable orbital and thermal evolution of Io is likely, if not required. If true, this would imply time-variable tidal heating of Europa as well, with obvious implications for the sustainability of its putative subsurface ocean and history of habitability. Indeed, an Io-dedicated mission that operates in the 2013-2022 timeframe could identify key parameters involved in orbital-thermal evolution that can be further investigated by the orbiters of the EJSM in 2025+.

Extrinsic Interest: What can we learn from Io about Earth and Solar System Volcanism?
Volcanism is a fundamental geologic process in planetary evolution, providing communication between the planet's interior and exterior. Volcanoes are thought to have a major role in bringing much of the Earth's volatile inventory to the surface, supplying the modern ocean and atmosphere. Much of the Earth's crust is made of volcanic and plutonic rocks. Studies of Io's volcanism can thus help us to understand terrestrial volcanism and crustal evolution.

Io's extreme heat flow is similar to the Earth's shortly after its formation, at the time life began, and thus Io provides a window into the Earth's formative years. This analogy became clear when the *Galileo* spacecraft detected that at least some of Io's lavas appear to have an unusually high eruption temperature, and may be similar to the high-temperature komatiite lavas that were common in the Earth's Archean Eon (3.85-2.5 Ga), but have been extremely rare in the past billion years. The present-day Earth contains several types of large igneous provinces such as flood basalts, which are manifestations of large-scale volcanism that (fortunately) have not occurred in historical times. Such eruptions can have devastating regional and even global effects, and have been implicated in mass extinctions. Eruptions on this scale occur much more frequently on Io, and are thus available for direct study. For instance, Io shows examples of large, compound flow fields that grow slowly by inflation (at e.g., Prometheus Patera), as well as rapidly-emplaced lava flow fields of comparable size resulting from short-lived "outbursts" (at e.g., Pillan Patera), as well as periodically overturning lava lakes (at e.g., Loki Patera).

The other terrestrial planets, particularly the Moon, Mars, and Venus, have undergone similar massive volcanic eruptions in the past, so Io's modern-day eruptions will teach us much about the history of these bodies. Analogies to the Moon, and possibly Mercury, may be particularly instructive because these bodies all have tenuous atmospheres, low gravity and lack Earth-like plate tectonics.

Extrinsic Interest: Atmosphere
Io's atmosphere is different from any other in the Solar System. It has a central role in both the Jovian magnetosphere (as the buffer of escaping material) and in shaping Io's surface (through frost condensation). It provides a fundamentally contrasting case study for several reasons. First, because Io's atmosphere is so closely coupled to its surface temperature via vapor pressure equilibrium (VPE) of SO_2 gas, and because the VPE of SO_2 varies by at least 6 orders of magnitude for the various temperatures appropriate for Io's surface (i.e., day, night, volcanic hot

spots), Io's atmosphere provides access to a temperature-pressure regime unlike any other known atmosphere. Strong horizontal winds that reach hundreds of meters per second result from volcanic plume collapse, and circum-planetary sublimation/condensation carries SO_2 towards regions of lower pressure. Vertical transport is also rapid, so that volcanic material reaches the exobase almost immediately. Sulfur dioxide vapor condensation and sublimation cycles are important and contribute to the heterogeneous distribution of surface materials and surface spectral reflectance of Io. From Io neutral cloud and torus observations, *Galileo* observations of Io's aurora, and from thermodynamic models of high-temperature magma-vapor equilibrium, we know that other volatile constituents are also involved in plume emissions and probably also are included in various volatile cycles on Io, but these are poorly understood. Many volcanic plumes exceed the scale height of the atmosphere. Second, unlike other atmospheres, Io's position deep within the Jovian magnetosphere, surrounded by a dense co-rotating plasma torus of heavy ions, leads to a wide variety of non-thermal processes involving charged particles that affect the surface and atmosphere, and ultimately nearly every other aspect of the Jovian magnetosphere, including the other satellites. These conditions challenge, and therefore ultimately extend, our ability to understand basic plasma and atmospheric physics.

Extrinsic Interest: Magnetospheric interaction

Io's interaction with the Jovian magnetosphere is quite complex. For example, currents flow between Io and the planet that are Mega-Amperes in strength. These currents must close through the body or its immediate surroundings, and it is not well understood how this occurs. These so-called Alfven wing currents also contribute to an Io footprint and tail in the Jovian aurora over a wide range of wavelengths. Furthermore beams of particles have been observed at and near Io and have been associated with downward currents. Io is also a strong source of neutral particles and dust through its volcanism. Many neutrals escape from Io and form an extended cold gas torus around the planet. This torus likely extends to the radial distance of Europa's orbit. Some of the neutrals from Io are ionized, producing both dramatic aurora over active hot spots, and a plasma torus that - because it is confined by Jupiter's magnetic field - is constantly impinging on the satellite with ion velocities of ~57 km/sec. Iogenic heavy ions dominate that plasma throughout much of the Jovian system. *New Horizons* has detected Iogenic particles in the magnetotail of Jupiter, thousands of Jovian radii from the planet, over a wide range of energies. Io is also deep within the Jovian radiation belt. This means its surface is subjected to a continuous flux of energetic ions and electrons that can modify the surface materials in several ways. Sputtering may redistribute materials on the surface and populate the atmosphere or the gas torus. Weathering by energetic electrons create new species in the surface.

The coupling between distinct plasma populations (i.e., the Io plasma torus and Jupiter's ionosphere) is a fundamental and unresolved problem in space physics. In many cases, coupling is imperfect due to an electric field component parallel to the ambient magnetic field. Parallel electric fields inhibit the propagation of the momentum-transferring Alfven wave and a magnetic decoupling (or violation of the frozen-in condition) results. Perhaps the most familiar example of a decoupled system is the Earth's magnetosphere-ionosphere system where the decoupling is manifested by electron acceleration and the formation of discrete aurora. Likewise, the Io-Jupiter system is at least partly decoupled by parallel electric fields that are manifested by auroral emissions in Jupiter's atmosphere at the base of Io's flux tube. The persistence of auroral emissions wakeward of Io's flux tube suggests that decoupling persists for a significant period of time following the initial interaction of a given flux tube with Io. Io's magnetospheric interaction

is therefore highly appealing for studying the general problem of coupling and electron acceleration processes.

As noted above, Iogenic plasma completely dominates the Jovian magnetosphere, and via sputtering and implantation, has a major influence on the surfaces of the other Galilean satellites. Io creates the plasma environment of Europa, which creates Europa's atmosphere. Of course both moons are deep within the Jovian radiation belts. Like the Van Allen belts at Earth, the belts are stable with intense populations of very energetic electrons and ions. The Jovian radiation belts are orders of magnitude more intense than those of Saturn. Because the belts contain energetic protons, oxygen and sulfur ions, it is not clear how much each source (planet, Io, solar wind, etc.) contributes. We do not understand what processes are involved in accelerating Iogenic plasma and other particles to these energies. These questions are important because they relate to the processing of Io's surface and that of the other inner moons. It will not be possible to fully interpret results from the EJSM without a good understanding of Io and its various influences on Europa. It is even possible that Iogenic plasma provides a source of chemical energy for possible Europan life.

Finally, the unique spectral signatures and large spatial scale of emission from a plasma-rich planetary magnetosphere provides a possible means of detecting and characterizing extrasolar planetary systems, increasing the importance of understanding the physics of such systems.

II. OUTSTANDING QUESTIONS AND SCIENCE OBJECTIVES FOR IO

Despite observations of Io by the *Voyager* (1979; 1980), *Galileo* (1995 – 2003), *Cassini* (2000), and *New Horizons* (2007) spacecraft, and ongoing ground-based monitoring, there are many important outstanding questions about Io. These include:

1. What is the compositional range of Io's magmas?
2. What is the composition of the core?
3. What is the magnitude and spatial distribution of Io's total heat flow?
4. What is the thickness of the lithosphere?
5. How does volcanism operate in extreme environments?
6. How do Io's very large volcanoes work?
7. What is the contribution of sulfur volcanism to Io's heat flow and surface features?
8. What is the full range of thermal anomalies on Io?
9. What is the current state of Io's internal heating regime?
10. Where is tidal heat being dissipated in Io's interior?
11. What is the degree of deformation caused by tidal stresses?
12. What are the minor constituents and dynamics of the atmosphere?
13. What source dominates the atmosphere, volcanism or sublimation, and how does it vary between day side and night side?
14. Is Io's ionosphere global, does it vary, and how is it maintained?
15.

Various concept studies for Europa orbiter and Jovian system missions during the past decade have resulted in a definitive set of science goals for future observations of Io by spacecraft. These include understanding the composition and level of differentiation of the interior, determining the mechanisms responsible for the formation of its surface features, finding the composition, origin, evolution and mode of transport of surface materials, and determining the compositional and temporal evolution of the Ionian atmosphere. Below we list the fundamental science goals in bullet form, then discuss in detail the observations and measurements required to advance our understanding of Io.

Science Objectives

The previous Solar System Decadal Survey [*Belton et al.*, 2002] identified four broad crosscutting themes: (1) The first billion years of Solar System history; (2) Volatiles and organics; (3) The origin and evolution of habitable worlds, and (4) Processes: How planets work. Io is perhaps the ideal target for studying how planets work since it is a world that evolves significantly over human timescales. The tidal heating that drives Io's activity is also a key process in controlling the habitable zone in the Jovian system and presumably other planetary systems throughout the universe [*Jackson et al.*, 2008]. Io may also provide clues to understanding the first billion years of Solar System history since ancient voluminous and high-temperature volcanic processes on the Earth, Moon, Mercury, and Mars are active on Io today. Io has also been used as an analog to understand volcanic processes on Venus [*Stevenson and McNamara*, 1988] and to understand the onset of plate tectonics [*O'Neill et al.*, 2007]. Discerning how Io became devoid of water and carbon but retained sulfur can instruct us about the evolution of volatiles essential for life as we know it. A *New Frontiers*-class Io mission was a high priority in the Decadal Survey for the next decade (2013-2022), an opinion seconded by the NRC study on choices for the next New Frontiers AO [*Beebe et al.*, 2008]. This report listed 7 science objectives for an 'Io Observer' mission, not in priority order:

1. Determine the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of Io's tidal heating. (We would like to add "and implications for the coupled orbital-thermal evolution of Io and Europa.")
2. Determine Io's interior structure, e.g., whether it has a magma ocean.
3. Determine whether Io has a magnetic field.
4. Understand the eruption mechanisms for Io's lavas and plumes and their implications for volcanic processes on Earth, especially early in Earth's history when its heat flow was similar to Io's, and elsewhere in the solar system.
5. Investigate the processes that form Io's mountains and the implications for tectonics under high-heat-flow conditions that may have existed early in the history of other planets.
6. Understand Io's surface chemistry, including volatiles and silicates, and derive magma compositions (and ranges thereof), crustal and mantle compositions and implications for the extent of differentiation, and contributions to the atmosphere, magnetosphere, and torus.
7. Understand the composition, structure, and thermal structure of Io's atmosphere and ionosphere, the dominant mechanisms of mass loss, and the connection to Io's volcanism.

Magnetic/electrodynamic interactions with Io have also been considered a high priority by the Heliospheric and Space Physics decadal survey. We suggest adding an eighth objective:

8. Investigate the neutral and plasma densities and energy flows in the Io plasma torus, plus their variations over time, and characterize the ionic radiation belts in the vicinity of Io and their influence on the surface.

II. OTHER KEY POINTS

- It is clear that Io has a metallic core. The size of the core is uncertain mainly because we do not know its chemical composition. An estimation of the size of Io's core would fix its density and by inference lead to a determination of core composition, i.e., core sulfur content. Another basic unknown about Io's core is its physical state, i.e., liquid or solid or partially molten. Additional knowledge of the physical state of the core would enable understanding of why Io has no magnetic field.

- The state of Io's mantle is also unclear. Eruption temperatures estimated from *Galileo* data would indicate that the mantle is largely molten. But such high degrees of melting would not allow sufficient tidal dissipation to explain the observed heat flow. One possibility is that Io's mantle is currently much hotter than an equilibrium model would allow. Alternatively, the magma may become superheated as it rises through the lithosphere, or the temperature estimates are incorrect. All three hypotheses must be explored and new data is clearly needed.
- Io's heat flow is so prodigious that it can be measured remotely, by quantifying Io's emitted infrared radiation. Steady-state tidal heating rates, as constrained by historical observations of Io's orbital evolution, suggest heat flow should be ≤ 1 W m^{-2}, except for a recent study suggesting that the observed ≥ 2 W m^{-2} heat flow is in fact consistent with Io's measured orbital evolution [*Lainey et al*., 2009]. Possible solutions to this discrepancy (if real) include coupled variations in Io's heat flow, internal rheology variations, and orbital elements (that would necessarily also involve Europa), or episodic release of heat despite constant tidal input, due to convective instabilities. More precise estimates are sorely needed to address these questions.
- Io's surface composition remains mysterious. SO_2 frost is the only constituent that has been definitively identified on Io's surface. Less conclusive evidence suggests the presence of: atomic and ionized S, O, Na, Cl, and K in the Io torus and neutral clouds; elemental cyclo-octal sulfur (S_8), and/or S_2O and polysulfur oxides; a possible 0.9-μm absorption feature tentatively identified as a Mg-rich silicate (e.g., pyroxene) observed in some of the dark spots; an absorption band at 3.915 μm that has been tentatively identified as pure solid H_2S or Cl_2SO_2 diluted in solid SO_2; and an enigmatic broad 1-1.5 μm band. Candidates for the red plume deposits and other red materials include S_3-S_4, S_2O, Cl_2S, and elemental sulfur contaminated by As, Se, or Te. The dominant Na-, Cl-, and K-bearing surface constituents are still uncertain, although NaCl, KCl, and perhaps alkali sulfides are favored. Many outstanding questions about Io's surface composition remain. Future Io missions require orbital spectrometers covering the visible and infrared at higher spectral and spatial resolution than earlier data sets.
- Specific questions exist to understand tectonic processes: 1) What is the thickness and composition of the crust? 2) What creates and destroys Io's mountains? and 3) How do tectonism and volcanism interact? To answer these questions, we need global panchromatic imaging at ~100 m/pixel, along with topographic data (at least 100 m vertical precision), and ≥4-color data at a similar resolution.
- After three decades of study, new questions with broad implications have arisen about Io's volcanism, including: 1) How does volcanism operate in extreme environments? (Io is the only place in the solar system where we can observationally test physical models of silicate volcanism that can be applied to Venus, the Moon, Mars, and asteroids.) 2) What is the compositional range of Io's magmas? 3) How does volcanism change as the scale of the eruption increases beyond that seen in historical eruptions on Earth? 4) What is the full range of Io's volcanic processes?
- Better constraining the cratering rate on Io would provide the details needed to derive the actual resurfacing rate, and an estimate of the rate of transfer of Ionian material to Europa's icy surface due to cratering events.
- Many major unsolved questions persist about Io's atmosphere, including: 1) What is the main atmospheric source, volcanism or recycled surface frost, and what is the dominant volcanic

effluent gas? 2) What gases other than SO_2, SO, and S_2 are present in the high- and low-pressure regions, and how do they interact? 3) By what mechanisms are the various visible and UV emissions excited? 4) How is the ionosphere maintained, and is it global or local? 5) Do particulate aerosols, visible in the plumes, interact with the atmosphere and provide less volatile constituents such as Na and Cl to the atmosphere and magnetosphere? Are the plumes the main source of Io's dust streams? 6) Is the upper atmosphere greatly expanded by the magnetosphere-atmosphere electrodynamic interaction, as predicted by models? 7) Are there local high-current electrodynamical interactions at the plumes, and if so, do they affect the plumes or atmospheric mass loss? 7) How does SO_2 that condenses out at the poles get recycled back into the atmospheric circulation? Why are there no extensive polar caps?

- We need to monitor variations in Io's atmosphere while simultaneously monitoring changes in torus properties. This requires *in situ* measurements of the ion and electron 3-d velocity distributions. To understand the coupling between the torus plasma and Jupiter's rotation we need to measure the heretofore unexplored high latitude regions between the torus and the planet with polar orbiting spacecraft.

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